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CALIFORNIA INSTITUTE OF TECHNOLOGY
Pasadena, California 91125

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Principal Investigator: Anatol Roshko
Anatol Roshko
Theodore von Kármán
Professor of Aeronautics, Emeritus

Graduate Aeronautical Laboratories
Division of Engineering & Applied Science
California Institute of Technology
Pasadena, California 91125

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Comparison of laboratory experiments and computational results for two dimensional flows showed that, in impulsively started flows, laboratory flows are two dimensional in the early stages and that three dimensional effects develop after acceleration is complete. In fully developed flow the mean and fluctuating forces are considerably lower (up to 50%) in the laboratory flows (ie with three dimensionality) than in the two dimensional numerical simulations. The experiments in tow tank and water tunnel also revealed the existence of long-time modulations of vortex shedding forces. These have the form of bursts with duration of order 10 vortex shedding periods.

A novel method of introducing *controlled* spanwise components of velocity into otherwise two dimensional flow, at low Reynolds number was to give the cylinder an axial (spanwise) motion, either a steady translation or a periodic oscillation. For unsteady, periodic axial oscillation of the cylinder, the experiments showed how the ratio of the spanwise period to the vortex shedding period determines the patterns of vortex dislocation in the wake, how regimes of chaos are formed and how shedding frequency and wake spectra are affected.

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RESEARCH ON BLUFF-BODY VORTEX WAKES

1. SUMMARY

A coordinated experimental and computational program of research was conducted on the near wakes of vortex-shedding bluff bodies, with and without forced oscillation.

2. OVERVIEW

The research accomplished is discussed in Section 3; publications and reports resulting from the research are listed in Section 4; personnel participating in the research are listed in Section 5; and Section 6 shows recognition accorded participants, through honors and awards.

3. DISCUSSION

Computational techniques based on vortex methods were developed and improved. Low-order, point vortex (inviscid) models were used to study flows past a flat bluff plate and compared with experimental results from a tow tank and water tunnel. Improvements to the computational technique included the incorporation of viscous effects and a fast algorithm. These were used to obtain accurate solutions of the Navier-Stokes equations at low to medium values of Reynolds number for flow past steady and rotary oscillating circular cylinders. These results are reported in the thesis of Koumoutsakos (1992) and the papers by Koumoutsakos and Leonard (1993, 1995). Interactions between shedding vorticity and a bluff plate oscillating in its own plane were investigated with a point-vortex computational technique (Cortellezi, 1992; Cortellezi *et al.*, 1993, 1994). Further computational developments included contributions to vortex particle methods for three-dimensional, unsteady flow (Winckelmans and Leonard, 1993) and fast parallel-tree codes (Salmon *et al.*, 1994).

Laboratory experiments were aimed mainly at elucidating effects of *three dimensionality*, due to end effects or to intrinsic instability. Comparisons with computational results for two dimensional flows showed that, in impulsively started flows, laboratory flows are two dimensional in the early stages and that three dimensional effects develop after acceleration is complete. The time to reach a fully developed vortex shedding condition is long (more than 50 flow times d/U) in both computational and laboratory flows. In the fully developed flows the mean and fluctuating forces are considerably lower (up to 50%) in the laboratory flows (ie with three dimensionality) than in the two dimensional numerical simulations. Experiments to reduce three dimensional motions, by placing the cylinder in a flow with stable stratification spanwise, gave an increase in drag but the available stratification was apparently insufficient to eliminate all spanwise motion. The experiments in tow tank and water tunnel also revealed the existence of long-time modulations of vortex shedding forces. These have the form of bursts with duration of order 10 vortex shedding periods. The above results are reported in the thesis by Lisoski (1993) while early parts are in the paper by by Chua, Lisoski, Leonard and Roshko (1990).

Further investigations of the effects of three dimensionality were made with a novel method of introducing *controlled* spanwise components of velocity into otherwise two dimensional flow, at low Reynolds. This has the effect of introducing streamwise vorticity into the wake. The method is to give the cylinder an axial (spanwise) motion, either a steady translation or a periodic oscillation. The results for a steady axial translation give new insights into the effects of yaw; a new physical model for such effects, based on vorticity concepts was developed (Lewis, 1992; Lewis and Gharib, 1993). For unsteady, periodic axial oscillation of the cylinder, the experiments showed how the ratio of the spanwise period to the vortex shedding period determines the patterns of vortex dislocation in the wake, how regimes of chaos are formed and how shedding frequency and wake spectra are affected (Hammache and Gharib, 1992).

Another part of the research was aimed at obtaining insights into (two dimensional) *near wake dynamics* by controlling or interfering with the shedding vortices. On the computational side this was effected in the numerical experiments of Cortellezi and Leonard, mentioned in the first paragraph, above. They studied unsteady flow past a semi-infinite plate at 90° with forcing bilateral movement of the plate and demonstrated that after the initial vortex was shed a unique forcing protocol is possible such that no further circulation is shed for a finite time interval. We expect that such a strategy should minimize the drag. Experiments in a wind tunnel were addressed to the effects of splitter plates, of various porosities, placed on the centerplane downstream of a circular cylinder. Decreasing porosity (increasing solidity) tends to move the vortex formation region downstream, thus reducing the base suction and the drag; for a solid plate, the overall reduction is from $C_D \doteq 1.2$ to 0.8 (Cardell, 1993). The important role of instabilities in the separated free shear layers was also demonstrated. The role of the free shear layers, especially in defining "Reynolds-number effects", was incorporated in a model of the mean flow (Roshko, 1993; 1995). With increasing Reynolds number the shear-layer thickness decreases, instability and transition occur earlier (in distance scaled on cylinder diameter) and the level of stress increases. This has the effect of decreasing the vortex formation length, thereby increasing the suction, drag and fluctuating lift (cross force).

Results of earlier work sponsored by the Ocean Engineering Program, on flow past rough circular cylinders at large Reynolds numbers, were reported (Shih *et al.*, 1993).

4. PUBLICATIONS

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Cardell, Gregory Scott (1993) Flow Past a Circular Cylinder with a Permeable Wake Splitter Plate. Ph. D. thesis, California Institute of Technology, Pasadena.

Chua, K. (1990) Vortex Simulation of Separated Flows in Two and Three Dimensions. Ph. D. thesis, California Institute of Technology.

Chua, K., Lisoski, D., Leonard, A. and Roshko, A. (1990) A Numerical and Experimental Investigation of Separated Flow Past an Oscillating Flat Plate, in *International Symposium on Nonsteady Fluid Dynamics*, J. A. Miller, and D. P. Telionis (eds.), ASME Fluids Eng. Div. Vol. 92, 455–464.

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Koumoutsakos, P. (1992) Direct Numerical Simulations of Unsteady Separated Flows Using Vortex Methods. Ph. D. thesis, California Institute of Technology, Pasadena.

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Winckelmans, G.S. and Leonard, A. (1993) Contributions to vortex particle methods for the computation of three-dimensional incompressible unsteady flows, *J. Comput. Phys.* **109**, 247–273.

5. PERSONNEL

Principal Investigators:

Anatol Roshko, Theodore von Kármán Professor of Aeronautics
Morteza Gharib, Professor of Aeronautics
Anthony Leonard, Professor of Aeronautics

Visitors:

Professor George Karniadakis

Students:

Kiat Chua	Ph. D. 1990	Research Associate, U.S. Electric Car Santa Rosa, CA
Gregory Scott Cardell	Ph. D. 1993	Assistant Professor, Dept. of Mechanical & Aerospace Eng., Illinois Institute of Technology
Luca Cortellezzi	Ph. D. 1992	Postdoctoral Fellow, Mathematics Department University of California at Los Angeles
Petros Koumoutsakos	Ph. D. 1992	Research Associate, Center for Turbulence Research, NASA Ames, Stanford University, CA
Christine Lewis	Ph. D. 1993	Institute for Non Linear Studies University of California at San Diego, La Jolla, CA
Derek Lisoski	Ph. D. 1993	Research Associate, Aerovironment, Inc. Monrovia, CA
Flavio Noca		Graduate Student

6. HONORS AND AWARDS

Morteza Gharib	Associate Editor, J. Fluids Engineering, American Society of Mechanical Engineering.
	Executive Committee Member, American Physical Society.
Anthony Leonard	Visiting Scientist to the John von Neumann Supercomputer Center, Rutgers/Princeton, New Jersey, October-November, 1989.
	Midwest Mechanics Lecture Series, February-March, 1992.
	Southwest Mechanics Lecture Series, March/April 1991 (Southwest Mechanics Institute, University of Houston, Texas A&M, Southern Methodist University).
	Fellow, American Physical Society, 1993.

Anatol Roshko

L.S.G. Kovasznay Distinguished Lectureship, University of Houston, 1990.

Opening lecture at the XVIII International Congress of Theoretical and Applied Mechanics, Haifa, Israel, August 22–28, 1992.

Opening lecture at the Second International Colloquium on Bluff Body Aerodynamics, Melbourne, Australia, December 7–10, 1992.

Raman Chair award, Indian Academy of Sciences, 1993.

Honorary Fellow, Indian Academy of Sciences, 1994.

Theodore von Kármán Professor of Aeronautics, Emeritus, 1994.